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The Development and Validation of Command Schedules for SeaWiFS

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ABSTRACT

An automated method for developing and assessing spacecraft and instrument command schedules is presented for the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) project. SeaWiFS is to be carried on the polar-orbiting SeaStar satellite in 1995. The primary goal of the SeaWiFS mission is to provide global ocean chlorophyll concentrations every four days by employing onboard recorders and a twice-a-day data downlink schedule. Global Area Coverage (GAC) data with about 4.5 km resolution will be used to produce the global coverage. Higher resolution (1.1 km resolution) Local Area Coverage (LAC) data will also be recorded to calibrate the sensor. In addition, LAC will be continuously transmitted from the satellite and received by High Resolution Picture Transmission (HRPT) stations. The methods used to generate commands for SeaWiFS employ numerous hierarchical checks as a means of maximizing coverage of the Earth's surface and fulfilling the LAC data requirements. The software code is modularized and written in Fortran with constructs to mirror the pre-defined mission rules. The overall method is specifically developed for low orbit Earth-observing satellites with finite onboard recording capabilities and regularly scheduled data downlinks. Two software packages using the Interactive Data Language (IDL) for graphically displaying and verifying the resultant command decisions are presented. Displays can be generated which show portions of the Earth viewed by the sensor and spacecraft sub-orbital locations during onboard calibration activities. An IDL-based interactive method of selecting and testing LAC targets and calibration activities for command generation is also discussed.

INTRODUCTION

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) is scheduled to be launched aboard the SeaStar satellite in 1995 as one of the Earth Probes projects in Mission to Planet Earth. The principal goal of the SeaWiFS mission is to provide a global set of ocean chlorophyll concentration (ocean color) every four days. To achieve this goal, SeaStar will be launched into a nearly circular, sun-synchronous orbit at 705 km. The sensor will be mounted on a tilting platform which can be pointed 20 degrees fore or aft of nadir as a means of avoiding sun glint. Table 1 summarizes some of the key SeaStar/SeaWiFS specifications. Two sets of data will be recorded onboard and subsequently downlinked at the Wallops Flight Facility using the S-band frequency: Local Area Coverage (LAC) which has 1.1 km nadir resolution and a 2800 km swath width, and Global Area Coverage (GAC) which is LAC subsampled for every fourth pixel and every fourth line over a 1500 km swath. Recorded LAC data is used primarily for sensor calibrations. In addition, LAC data will be continuously broadcast using the L-band frequency to High Resolution Picture Transmission (HRPT) stations.

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Table 1. SeaStar/SeaWiFS specifications.

Orbit characteristics:	
	sun synchronous
	descending noon equatorial crossing
	98.2 degree inclination
	98.9 minute orbital period
	0.02 eccentricity
Instrument characteristics:	
	20 degree fore and aft sensor tilt
	116.6 degree scan width (LAC)
	8 bands (visible and near infrared)
	10 bit digitization
	6 scans/second

In a unique agreement between the private sector and NASA, Orbital Sciences Corporation (OSC) assumes responsibility for building, launching, and operating the instrument (SeaWiFS) and the spacecraft (SeaStar). NASA will then obtain data from SeaWiFS by means of a data purchase from OSC. This novel agreement was designed to deliver the spacecraft at a reduced cost and over a tighter schedule. To assist in meeting this goal, OSC has subcontracted Hughes/Santa Barbara Research Center (SBRC) to build the radiometric instrument. NASA/Goddard Space Flight Center (GSFC) is responsible for developing sensor and spacecraft command sequences to maximize the scientific usefulness of the data. The primary link to OSC is through SeaWiFS Mission Operations (MO) at NASA/GSFC which, among other tasks, is charged with the responsibility of ensuring the collection of GAC, LAC, and calibration data through the submission of weekly and daily command schedules to OSC.

Because of a stringent set of cascading directives developed for SeaStar/SeaWiFS operations, the problem of developing command schedules lends itself to a hierarchical set of algorithms. This in conjunction with an accurate orbit model and other operational inputs such as downlink times and instrument tilt times permit the development of modular software to generate complex command schedules. The command scheduler is similar in nature to the more generic rule-based expert system discussed in Hughes *et. al.* (1993). Figure 1 shows a generalized flow chart illustrating some of the logic used by the command scheduler. The scheduler is propagated in one second time increments to reflect the minimum command update frequency of the SeaStar system. This update frequency is also used in orbit propagations which are read by the command scheduler.

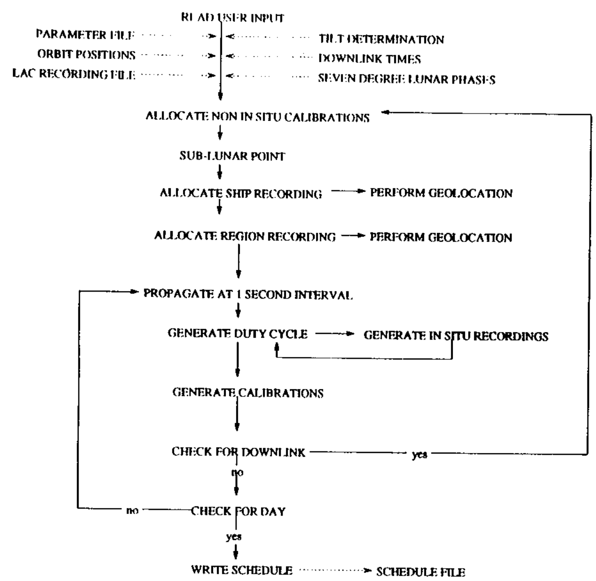

Figure 1. Flowchart illustrating the general processing stream of the command scheduler.

Description of scheduling rules

The primary goal of this mission is to obtain global coverage of ocean chlorophyll every four days. This is followed in order of importance by the acquisition of the recorded LAC which will be used primarily for instrument calibration and characterization. A summary of the SeaWiFS mission goals is listed below in descending order:

1. Record a global set of GAC data onboard
2. Transmit and acquire all recorded GAC data on the ground
3. Record LAC data of calibration targets with the following priorities:
    - lunar calibration
    - calibration using irradiances reflected off diffuser plate
    - detector performance
    - interchannel gain measurements
    - pre-selected ship/buoy and region targets
4. Transmit and acquire recorded LAC data on the ground
5. Broadcast real-time LAC data

AUTOMATED PRODUCTION OF COMMAND SCHEDULES

The command scheduler is a modularized FORTRAN program which reads previously generated orbit positions and creates time-ordered command schedules that meet the mission goals. FORTRAN was chosen as the software language for the production code to maintain consistency with existing orbit propagation models which are coded in this language (Patt *et. al.*, 1993). Orbit positions are read by the scheduler and are highly integrated into the functionality of the program. Orbit positions and instrument tilting times are produced by separate stand alone modules which are executed prior to initiating a scheduler run. These stand alone programs allow flexibility in creating scheduler inputs.

Outputs from the command scheduler are produced as daily and weekly ASCII files consisting of a time-ordered list of spacecraft and instrument commands. In addition, LAC and GAC recording log and error log files are also written by the scheduler. Commands are abbreviated to 16 byte strings to permit portability with PC programs which are currently under development. Table 2 lists all the commands produced by the scheduler. The American Standard Code for Information Interchange (ASCII) was chosen as the output format in part to allow quick visual verification.

Table 2. SeaWiFS commands.

COMMANDS	EXPLANATION
ACS Opn Loop On	Initiate lunar cal maneuver
ACS Opn Loop Off	Stop lunar cal maneuver
Chg Gain Band	Change gain
Chg TDI Band	Change detector configuration
Chg Tilt Aft	Point sensor back
Chg Tilt Forward	Point sensor forward
Chg Tilt Nadir	Point sensor nadir
Recorder Dmp On	Initiate downlink
Recorder Dmp Off	Finish downlink
Elct Lun Cal On	Initiate lunar cal
Elct Lun Cal Off	Finish lunar cal
Elct Sol Cal On	Initiate solar cal
Elct Sol Cal Off	Finish solar cal
Elct TDI Cal On	Initiate detector cal
Elct TDI Cal Off	Finish detector cal
Elct Turn On	System electronics on
Elct Turn Off	System electronics off
GAC Partition	Partition recorder
GAC Recorder On	Initiate GAC recording
GAC Recorder Off	Finish GAC recording
LAC Recorder On	Initiate LAC recording
LAC Recorder Off	Finish LAC recording
LAC Xmitting On	Initiate LAC transmission
LAC Xmitting Off	Finish LAC transmission
Lun Cal Pitch Rt	Set lunar cal pitch rate
L-Bd Xmitter On	Turn on L-band transmitter
L-Bd Xmitter Off	Turn off L-band transmitter
Rst Nml Pitch Rt	Reset pitch rate
Rst Tilt Aft	Reset tilt to aft
Earth Mode On	Initiate Earth viewing mode
Sol Cal Mode On	Prepare for solar cal
S-Bd Xmit On	Turn on S-band transmitter
S-Bd Xmit Off	Turn off S-band transmitter

Table 3. Command sequences illustrating a typical duty cycle.

L-Bd Xmitter On	27	1	1994	84	604	2999	72.32	72.68
Elct Turn On	17	1	1994	84	634	2999	72.32	72.68
Earth Mode On	30	1	1994	84	639	2999	72.32	72.68
Rst Tilt Aft	29	20	1994	84	654	2999	72.32	72.68
Chg Gain Band 1	3	1	1994	84	659	2999	72.32	72.68
Chg Gain Band 2	3	1	1994	84	659	2999	72.32	72.68
Chg Gain Band 3	3	1	1994	84	659	2999	72.32	72.68
Chg Gain Band 4	3	1	1994	84	659	2999	72.32	72.68
Chg Gain Band 5	3	1	1994	84	659	2999	72.32	72.68
Chg Gain Band 6	3	1	1994	84	659	2999	72.32	72.68
Chg Gain Band 7	3	1	1994	84	659	2999	72.32	72.68
Chg Gain Band 8	3	1	1994	84	659	2999	72.32	72.68
Chg TDI Band 1	4	0	1994	84	660	2999	72.32	72.68
Chg TDI Band 2	4	164	1994	84	660	2999	72.32	72.68
Chg TDI Band 3	4	0	1994	84	660	2999	72.32	72.68
Chg TDI Band 4	4	26	1994	84	660	2999	72.32	72.68
Chg TDI Band 5	4	0	1994	84	660	2999	72.32	72.68
Chg TDI Band 6	4	74	1994	84	660	2999	72.32	72.68
Chg TDI Band 7	4	0	1994	84	660	2999	72.32	72.68
Chg TDI Band 8	4	161	1994	84	660	2999	72.32	72.68
GAC Recorder On	20	1	1994	84	663	2999	72.37	72.74
LAC Xmitting On	24	1	1994	84	664	2999	72.32	72.68
LAC Recorder On	22	1	1994	84	868	2999	60.88	60.36
LAC Recorder Off	21	0	1994	84	898	2999	59.14	58.55
Chg Tilt Forward	6	-20	1994	84	1846	2999	2.57	1.07
GAC Recorder Off	19	0	1994	84	3063	2999	-69.47	72.72
LAC Xmitting Off	23	0	1994	84	3064	2999	-69.52	72.78
L-Bd Xmitter Off	26	0	1994	84	3066	2999	-69.52	72.78
Elct Turn Off	16	0	1994	84	3067	2999	-69.52	72.78

Table 3 shows a command schedule segment for a typical duty cycle. On each line, the abbreviated commands appear on the left followed by a command code, configuration code, year, day of year, second of day, sub-orbital latitude, and sub-orbital solar zenith angle. Dummy values are used in this example for the command codes. The orbital duty cycle commences on each orbit when the solar zenith angle of the sub-orbital point exceeds a threshold value which is currently set to 72.7 degrees for a nominal SeaWiFS orbit. This provides balanced solar zenith angle coverage for a required 40 minute duty cycle per orbit.

Sun glint from the ocean surface can significantly contaminate radiances observed by remote sensors. SeaWiFS has the capacity to tilt 20 degrees fore or aft (toward the North Pole on the descending node) of nadir as a means of minimizing glint. On the descending orbit the instrument will be tilted 20 degrees aft as the duty cycle commences. Near the solar declination, the instrument will be tilted 20 degrees fore. Several tilting algorithms have been developed. The program TLTMNGLT minimizes sun glint by checking orbit position and sun angles to determine times of maximum sun glint. The instrument tilting times are then computed on an orbit-by-orbit basis. The program TLTMNFST provides a faster, less accurate determination of tilting time by using the same algorithm as TLTMNGLT to compute the orbital tilt time for the orbit closet to the midpoint of a day. The program then steps forward and backward in time using increments equal to the orbital period to determine other tilting times for an entire day. The current operational plan is to use the staggered tilting algorithm in the program STAGTILT which seeks to minimize sun glint and maximize Earth coverage using a four day cycle of shifting the tilt above the glint for two days and below the glint for two days (Gregg and Patt, 1994).

At the start of execution, the command scheduler prompts the operator for year, day of year, and number of days of the run. As an alternative, an operator can create a 'date.dat' file with the Unix command "date>date.dat". The scheduler checks if "date.dat" is present and contains the current date. If these conditions are satisfied, the scheduler extracts the date information and only prompts the operator for the duration of the run. In addition to these inputs, the scheduler is manipulated in part by inputs from a parameter file and daily LAC recorder files which are read by the scheduler. The former file contains values on scheduler operation specifications which change infrequently; the latter file contains information on ship/buoy and region targets and calibration frequencies used in allocating the flight recorder. Ships and buoys are handled identically by the scheduler and will be referred to simply as ships from this point on.

The most challenging aspect of command scheduling logic involves the allocation of the LAC flight recorder partition. The overall recording priorities used in the recorder allocations are listed under item 3 of Table 2. Lunar calibrations have top priority followed by solar calibrations, detector performance assessment, and interchannel gains performance assessment. Earth targets (ships, buoys, and regions) have lowest priority with ships having priority over regions. Detailed descriptions of calibrations are found in Woodward *et. al.* (1993).

The daily LAC Recorder File (Table 4) is read by the scheduler during the processing when a nocturnal downlink is encountered for an ascending pass (local midnight downlink). The timing is done so as not to interfere with potential LAC recording events. Each ship in the file has a corresponding longitude, latitude, priority, and recording duration in seconds. Each region has corresponding starting and ending longitude and latitude (defining a rectangular box) and a priority. The weekly frequency of solar, lunar, interchannel gain, and detector calibrations are also specified. The scheduler uses this information for allocating LAC recording space for each of the next two downlink recording periods. Ships and regions are each assigned priorities; the lower the value, the more likely a target will be recorded. All viewed ships are allocated before any region is allocated. In other words, the target with the lowest priority number has recorder space allocated first, followed by the target with the next lowest number, and so on. This means that the scheduler looks over the entire recording period and allocates recorder space on the basis of target priority rather than on the basis of target view time.

Table 4. Example of a typical LAC recording file. "In situ" precedes the number of ship targets which is followed by the ships with corresponding longitude, latitude, priority, and, recording duration (s). "Regions" precedes the number of region targets which is followed by the regions with corresponding longitudinal limits, latitudinal limits, and priorities. The weekly frequencies of solar, lunar, interchannel gain, detector calibrations are last.

Calibration Targets					
1994 84					
In-situ					
11					
Clark's Buoy		-156.3400	18.6700	1	30
Bermuda Buoy		-71.9000	32.1200	6	30
JGOFS		63.2500	19.4000	3	30
NOAA S. Atlantic Bight		-77.5200	32.0300	4	30
NOAA Gulf of Cal.		-107.2600	22.1100	5	30
S.Africa		10.2300	-32.8700	6	30
Galapagos		-92.6200	-3.2500	8	30
Gulf of Mexico		-86.8600	24.7900	3	30
Oregon St.		-131.1400	45.7700	4	30
Navy Bering Sea		-175.5800	63.4200	10	30
Pacific		175.0000	1.0000	11	30
Regions					
4					
Sargasso Sea	-70.0000	-45.0000	20.0000	30.0000	2
Gulf of Mexico	-110.0000	-80.0000	17.0000	31.0000	1
Galapagos Area	-105.0000	-75.0000	-15.0000	0.0000	3
Micronesia	135.0000	180.0000	0.0000	15.0000	4
Solar Calibration					
14					
Lunar Calibration					
1					
Intergain Calibration					
14					
TDI Check					
14					

Recorder partitioning

The onboard flight recorder has a storage capacity of 119.2 mb. A daily determination of GAC recording requirements is made by the scheduler during the processing of each local midnight downlink. This involves summing the total and partial duty cycles for the two subsequent recording periods. Using the maximum of these values, a section on the recorder is reserved for GAC and the remainder is reserved for LAC. Since this partitioning is performed once a day, the recorder is not fully utilized for the downlink with the shorter GAC recording period.

Lunar Calibrations

Current plans for onboard calibrations include a backorbit maneuver to scan the lunar surface near a full Moon event (using the closest orbit to a seven degree lunar phase angle). The seven degree phase angle was chosen as a means of enhancing the calibration consistency. A full Moon is defined at the point of the Moon's closest approach to the anti-solar point. The Moon was chosen as a calibration source due to its reflective stability compared to onboard calibration sources which can be expected to degrade with time. During lunar calibrations the spacecraft will pitch 360 degrees on the backorbit spanning a 40 minute period thus allowing the Moon to come into view of the sensor. This operation can, at best, be performed twice a month when the Moon is coming into and out of full phase.

Solar Calibrations

Unlike lunar calibrations which are restricted to particular orbits, solar calibrations can, in principle, be performed on any orbit. However to maintain consistency, solar calibrations are constrained to the first orbit of the GMT day and the orbit midway between the local midnight and local noon downlink. Solar calibrations are scheduled to occur as the spacecraft sub-orbital point makes its closest approach to the South Pole. For this operation the instrument is commanded to tilt aft 20 degrees and LAC data is collected along the back scan where the sensor views a solar diffuser plate. It is expected that these calibrations will provide high frequency instrument calibrations anchored by the more stable lunar calibrations.

Detector and interchannel gain checks

In general, these calibrations are identical to solar calibrations in terms of spacecraft location and sensor tilt configuration. The detector check will involve sampling each of the four detectors for each band as well as a combination of all four while scanning the solar diffuser plate. Interchannel gains will be checked by applying an electronic calibration pulse to each detector following the diffuser scan.

In situ calibrations

Recording of in situ targets for instrument calibrations involve the most complicated logic in the scheduler. The basic concept is to record data over a target coincident with the recording of data on a ship. Accurate geolocation algorithms are essential for the task of precisely recording specified coordinates on the Earth's surface. Geolocation algorithms which assume an ellipsoidal Earth and employ vector and matrix computation to enhance efficiently are used by the scheduler (Patt and Gregg, 1994). These algorithms were implemented and tested in the AVHRR/Pathfinder project.

Among the complexities with in situ recordings are Earth targets with overlapping recording periods, differing tilt configurations, variable record times and target priorities, and conflicts with HRPT visibility masks. LAC recording is blocked when an HRPT station is in view of the satellite since these data can be obtained through agreements with the HRPT facilities. In addition instrument tilts are deferred if a conflict occurs with a ship target. All these factors play a role in the allocation algorithms. All ship targets in view of the sensor scan are recorded as long as recorder space is available. The duration of each ship recording is specified in the LAC recording file. Any remaining recording space is then used for recording scans of region targets. A region is recorded as long as the central pixel of the scan is within the rectangular region area. Default regions are specified in the parameter file to insure complete usage of the LAC partition in the flight recorder. The size and location of the default regions are chosen by the Project Scientist by considering downlink orbits and viewing geometries.

SCHEDULE VERIFICATION AND DISPLAY

The Interactive Data Language (IDL) was used to produce software tools for the graphical display command schedule performance. IDL was chosen in part since this package provides tools for relatively easy development of graphical user interfaces (GUI's). These interfaces allow quick and mostly error-free updates of inputs to the verification programs.

Rapid Verification of the Recording of LAC Targets

An IDL package named PLOTDOWN (plot LAC recording for downlinks) was created to acquire a quick-look at the budgeting of LAC recorder space. Figure 2 shows the GUI for PLOTDOWN. In general, an operator selects the input files which specify the schedule, orbit propagation, and downlink times, and chooses one of the following types of plots:

PLOT ORBITS - plots only orbit tracks

PLOT ALL LAC SCANS - plot all LAC recording

PLOT IN SITU SCANS - plot ship and region recordings

PLOT SOLAR SCANS - plot spacecraft position for solar calibrations

PLOT LUNAR SCANS - plot spacecraft location for lunar calibrations

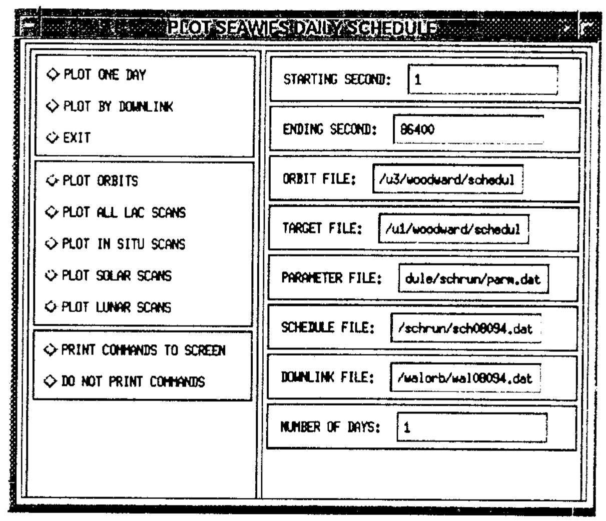

Figure 2. GUI for the program PLOTDOWN. An operator selects input files and plotting options to create plots of LAC scans.

A separate window is then created with an equi-rectangular projection of the Earth's continents and the specified type of plot is produced on this projection (Figure 3). This makes it possible for an operator to visually inspect the performance of the LAC partition in the onboard recorder.

Figure 3 illustrates two examples which illustrate the effects of some rules used in constructing command schedules with regard to in situ targets. Figure 3a shows that all the ships are recorded except those within the GSFC visibility mask. Figure 3b shows an unrecorded ship near the west coast of South America by the Galapagos Islands. This occurred as a result of lunar, solar, detector, and interchannel gain calibrations which supersede the ship during this recording period. In addition, the Galapagos ship was given a lower priority than the other ships that are viewed and recorded. The figures also illustrate another consideration for scheduling in situ recordings: due to the nature orbit tracks for polar orbiting satellites, ships and regions at higher latitudes have a higher recording frequency.

a)

b)

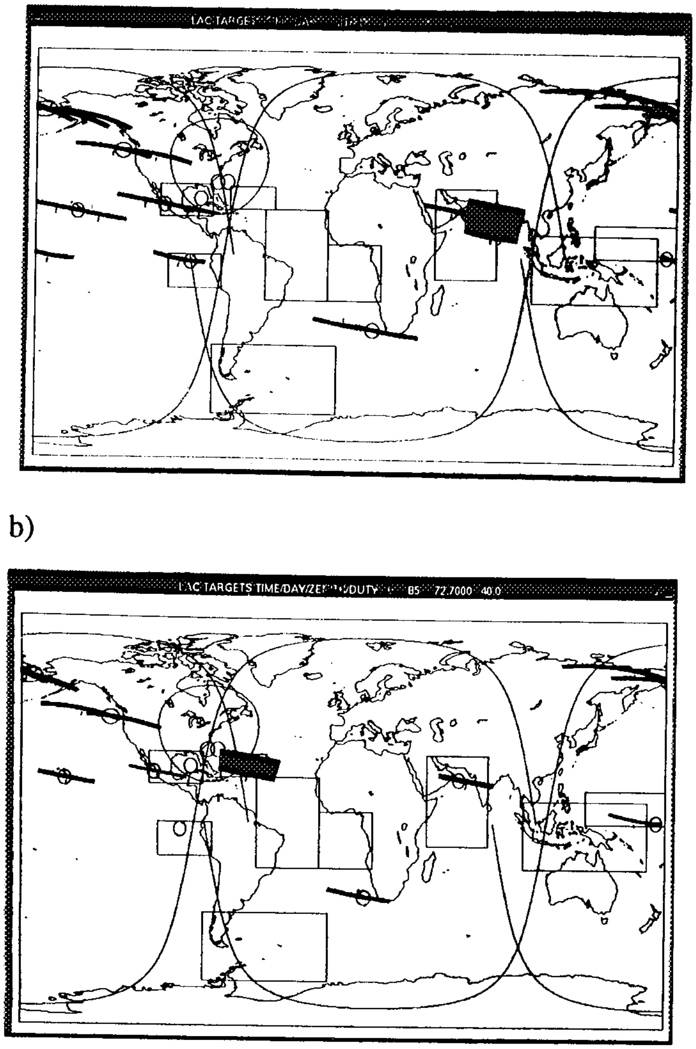

Figure 3. Two plots produced by PLOTDOWN illustrating LAC scans of the Earth's surface. Ships appear as small circles, regions as rectangles, HRPT visibility mask as a large circle. The orbit tracks for the two downlink orbits are also plotted.

Detailed Verification of Duty Cycle

A comprehensive examination of scheduling activities is essential to assure that the spacecraft/sensor systems are functioning properly. To assist in evaluating the command schedule an IDL package named COLOR_IT (create color-coded plots) was created. This utility can be used to produce a color-coded plot of the daily spacecraft and sensor operations. This allows for a visual inspection of the activities impacting the recorder including all GAC and LAC recordings. In addition, other aspects of the scheduling such as duty cycle initiation, Earth coverage, and tilt times can be visually verified. Figure 4 shows the GUI for COLOR_IT. An operator can first create the color palette to be used for differentiating scheduled activities. Input files can then be selected and a plot created.

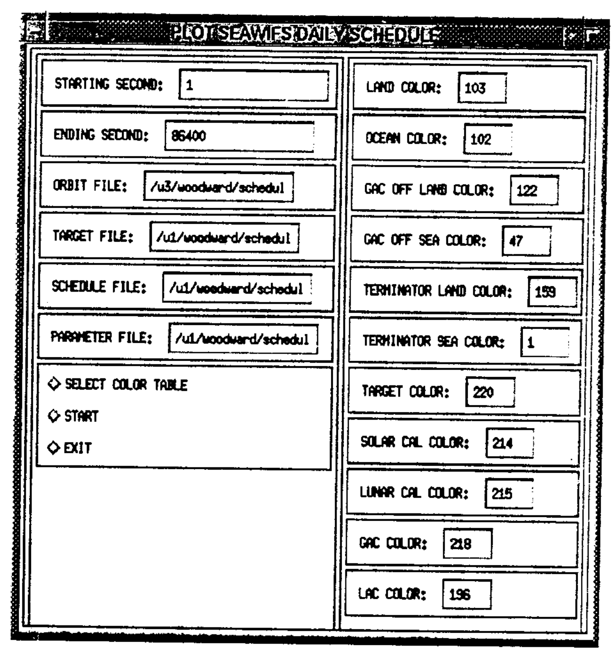

Figure 4. GUI for the program COLOR_IT. An operator selects input files and creates a color table.

INTERACTIVE UTILITY FOR MANAGING ONBOARD RECORDER

The IDL-based utility Calibration and validation Tool of Local Area Coverage (CATLAC) was developed by MO to assist the Calibration and Validation element of SeaWiFS in assigning LAC Earth targets and calibration frequencies (Woodward *et. al.*, 1994). In general, CATLAC permits a user to allocate and verify onboard LAC recorder space. This is done through an interactive display located in the GUI which allows an operator to graphically create ship and region targets and verify recording scenarios. Other calibration frequencies can also be specified and tested by spawning a command scheduler run and plotting the subsequent LAC recorder activity.

CONCLUSIONS

The utilities presented in this paper present some mechanisms for dealing with problems often encountered in the scheduling of activities with Earth-orbiting spacecraft. Many of the solutions are tailored specifically for SeaWiFS, but general applicability to other Earth orbiting systems is possible with minor modifications. Most of the IDL-based graphical utilities are in the process of being ported to separate graphics libraries on a Unix workstation and a PC.

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Operations

3. Control Centers

* *Presented in Poster Session*